ttV production in ATLAS

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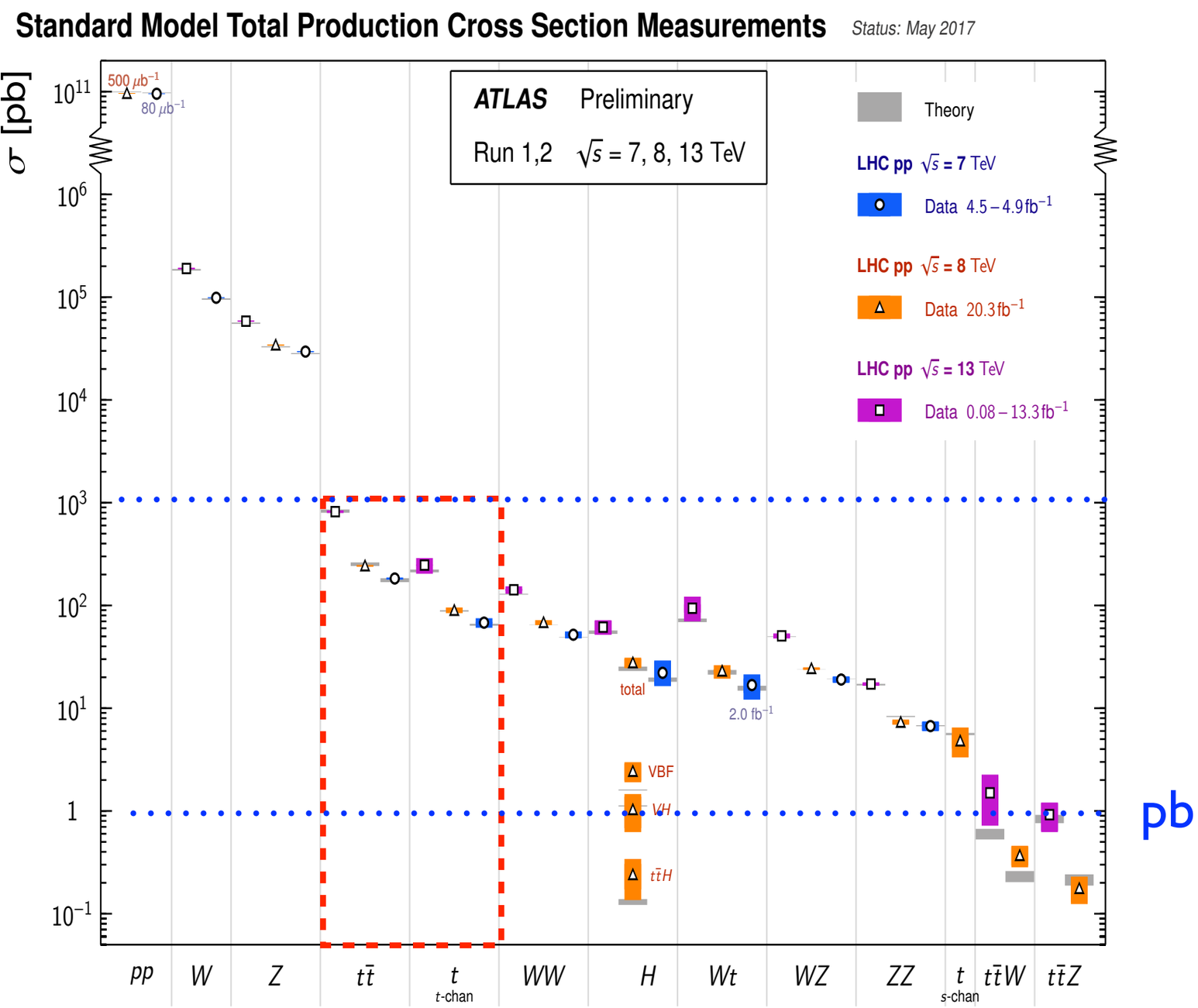
on behalf of the ATLAS collaboration

TOP2017

10th International Workshop on Top Quark Physics

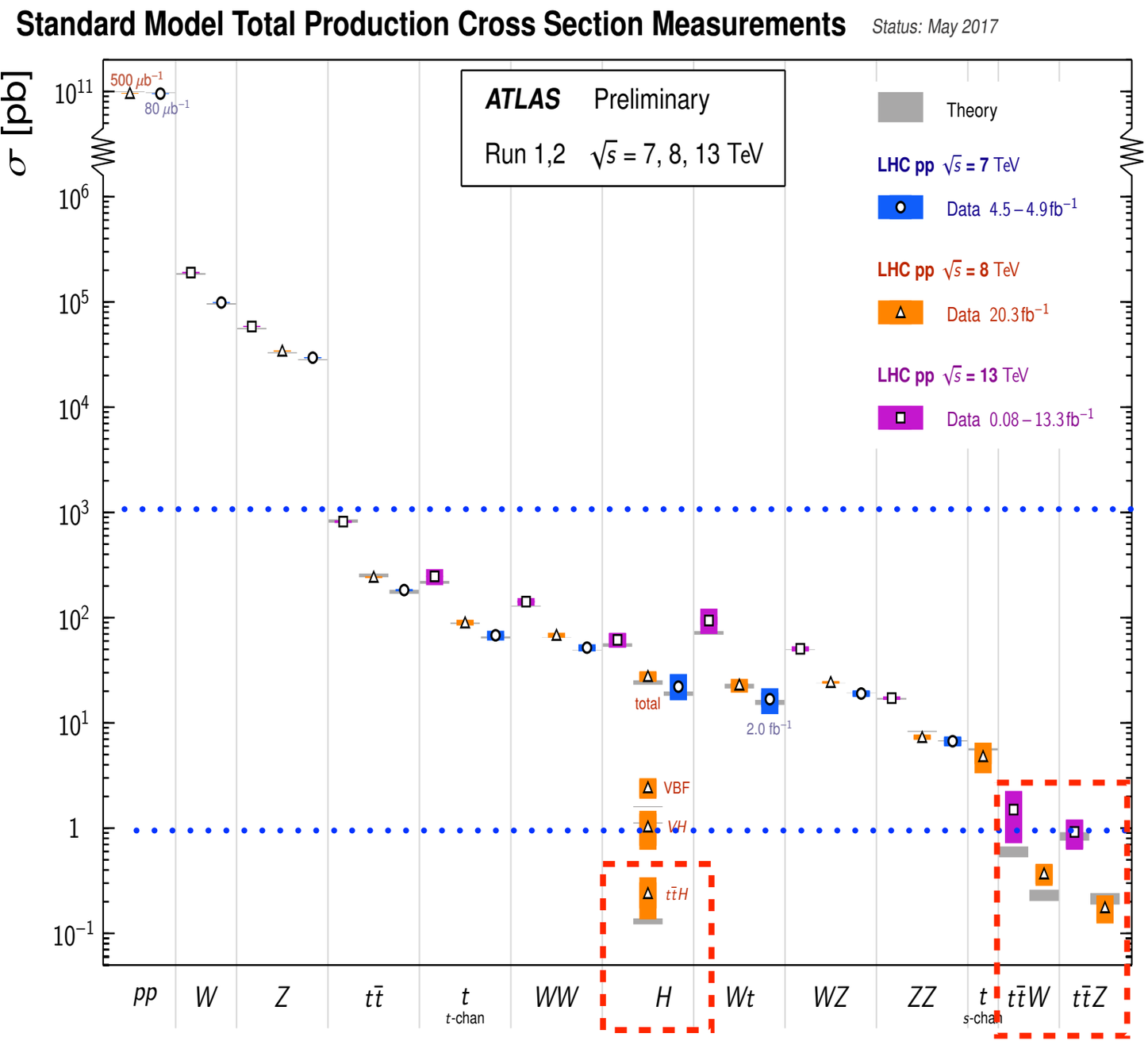
17 - 22 SEPTEMBER | BRAGA, PORTUGAL

From tt to ttX

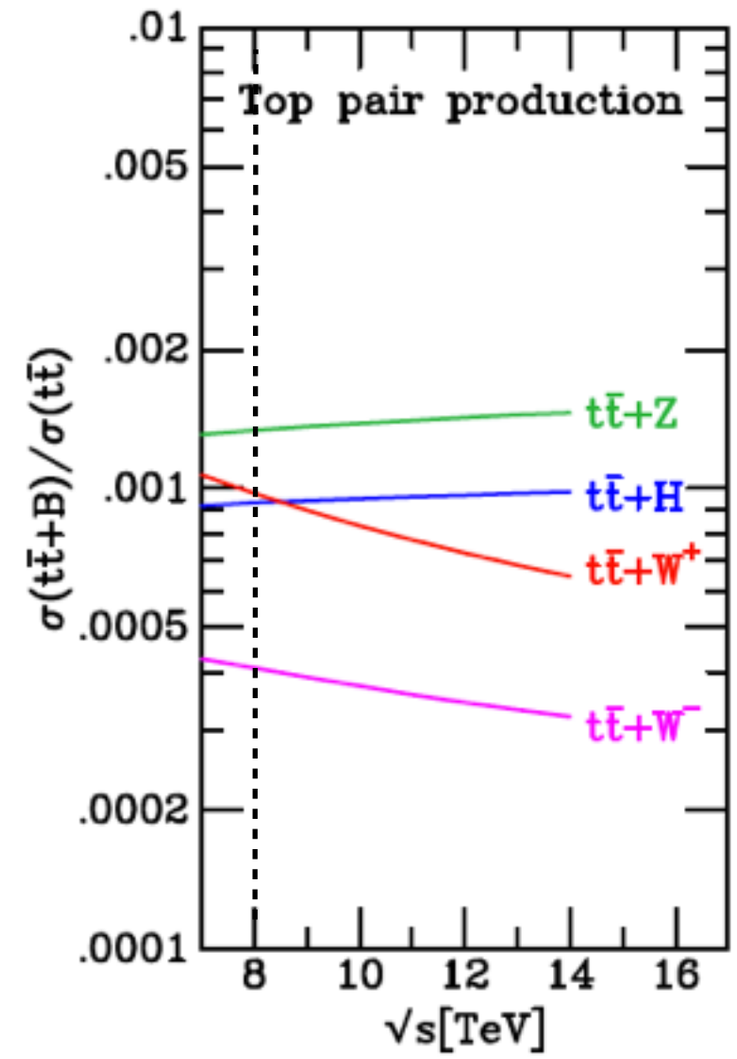


pb

From tt to ttX



arxiv.org/abs/1309.1947



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arXiv:1702.00800 [hep-ph]
scale uncertainties only

4-7% NLO+NNLL

8% NLO+NNLL

√s		7	8	13
$t\bar{t}$	pb	182	259	842
$t\bar{t}W$	fb	169	232	600
$t\bar{t}Z$	fb	137	206	840
$t\bar{t}H$	fb	86	130	530

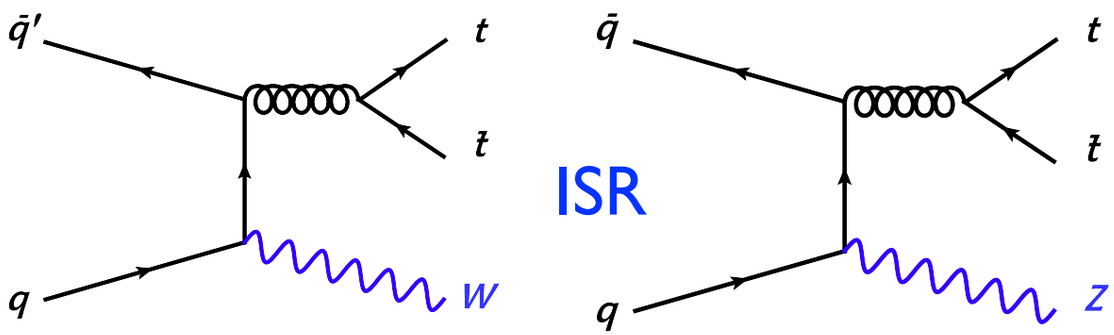
theory uncertainty

6% NNLO+NNLL

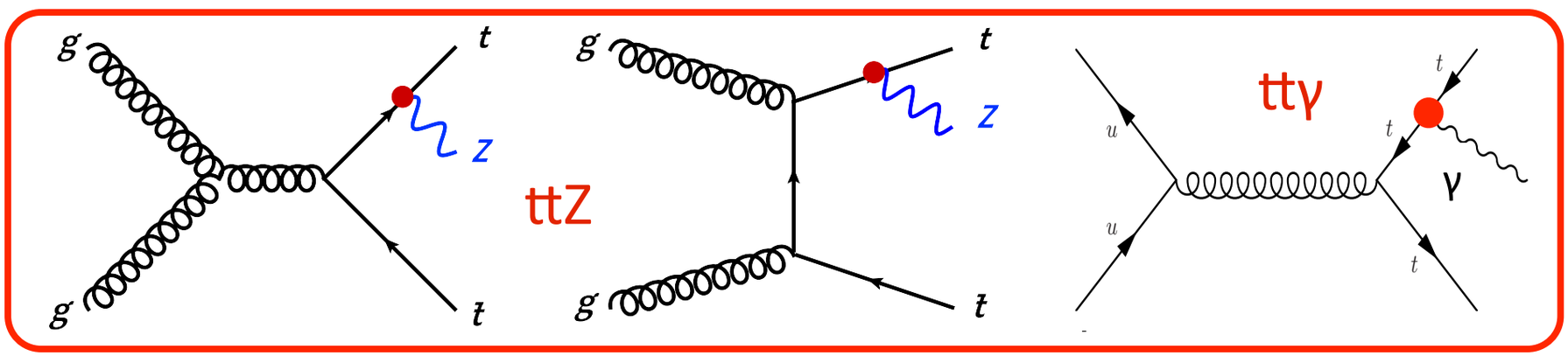
+7.8-5.5% NLO+NLL (YR4)

Production mechanisms and couplings

- Direct measurement of top coupling to gauge bosons via FSR
- It is sensitive to most of the leading EFT operators that preserve charge-parity and flavour in neutral-currents



FSR



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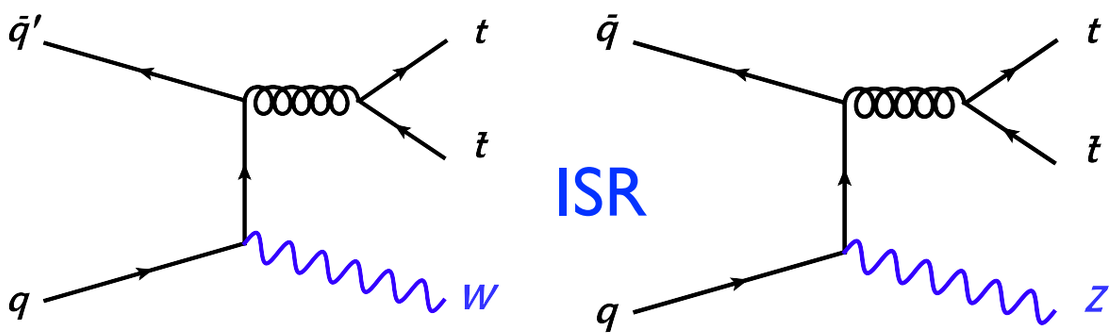

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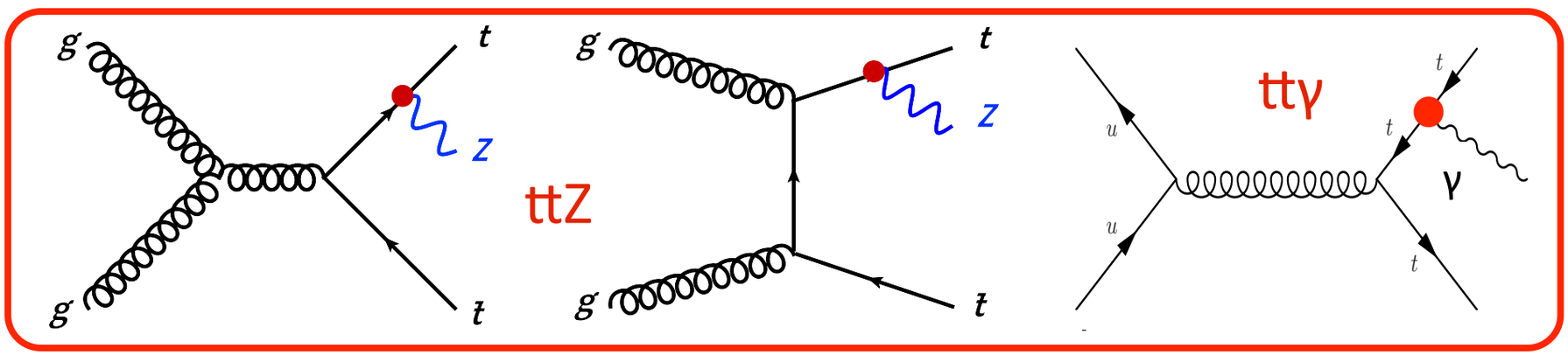
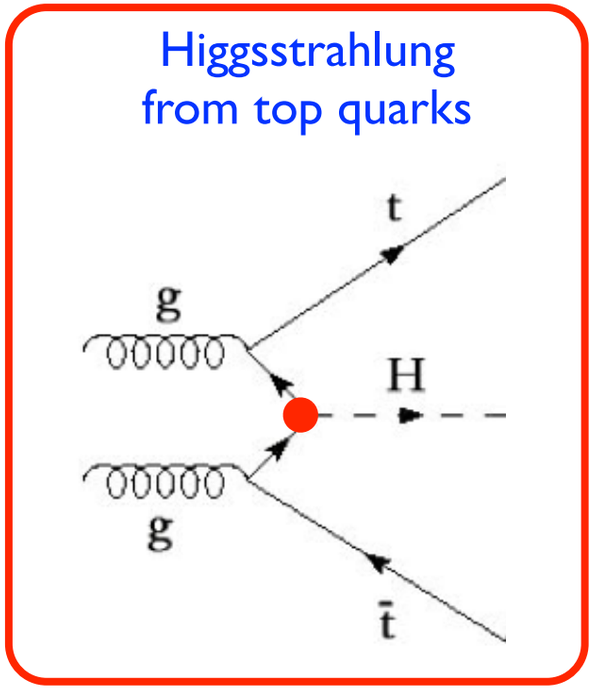




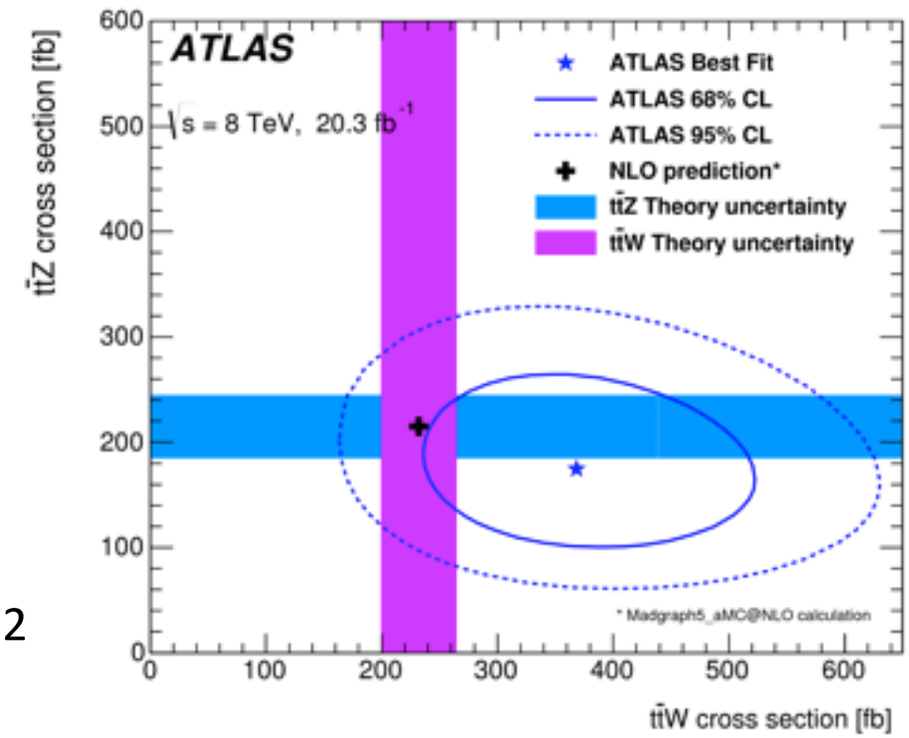
$$\sigma(t\bar{t}H) \propto g^2_{t\bar{t}H}$$

- Direct measurement of top-Higgs Yukawa coupling Y_t in $t\bar{t}H$ production
- $t\bar{t}W$ and $t\bar{t}Z$ are often dominant and irreducible backgrounds for many searches and for $t\bar{t}H$

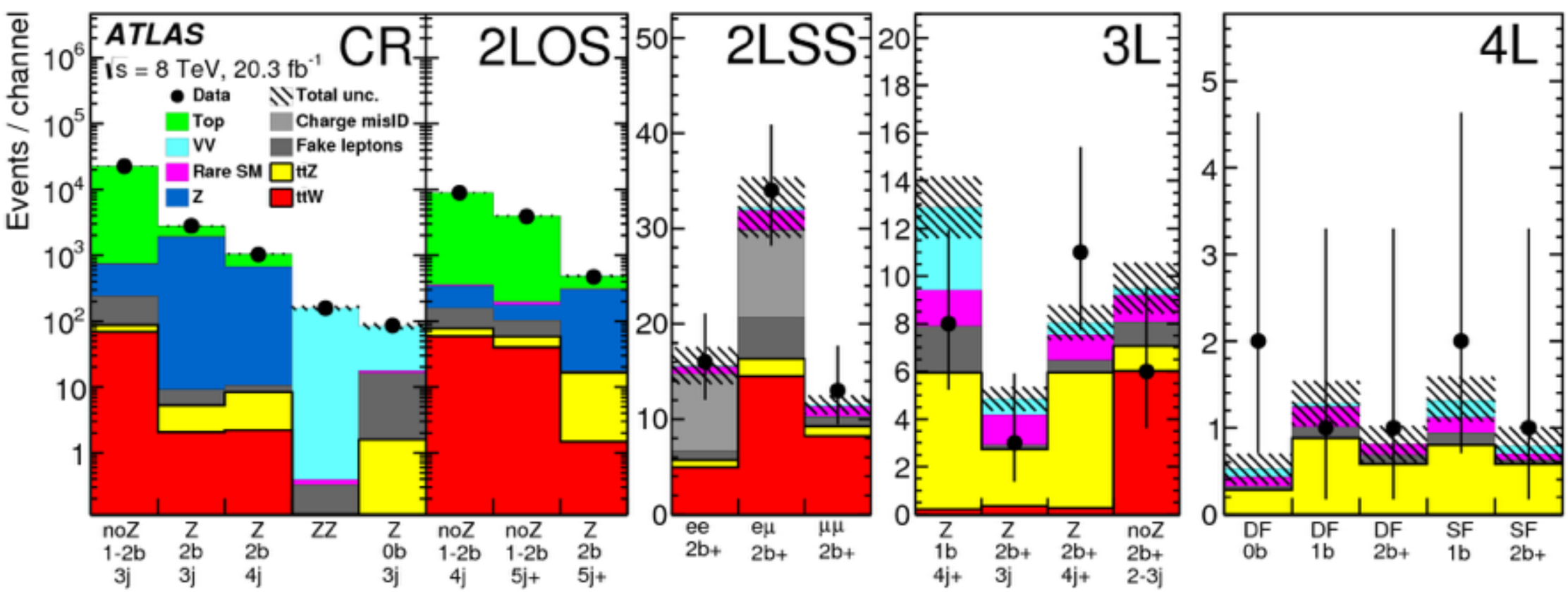
talks by Nedaa Asbah and Pietro Vischia tomorrow

Run I ttV measurement

- 4 channels
  - Cut and count analysis in all channels except for 2LOS
- Simultaneous fit in signal and control regions
- Significance of 5.0σ (4.2σ) over the background-only hypothesis for $t\bar{t}W$ ($t\bar{t}Z$)



JHEP 11 (2015) 172



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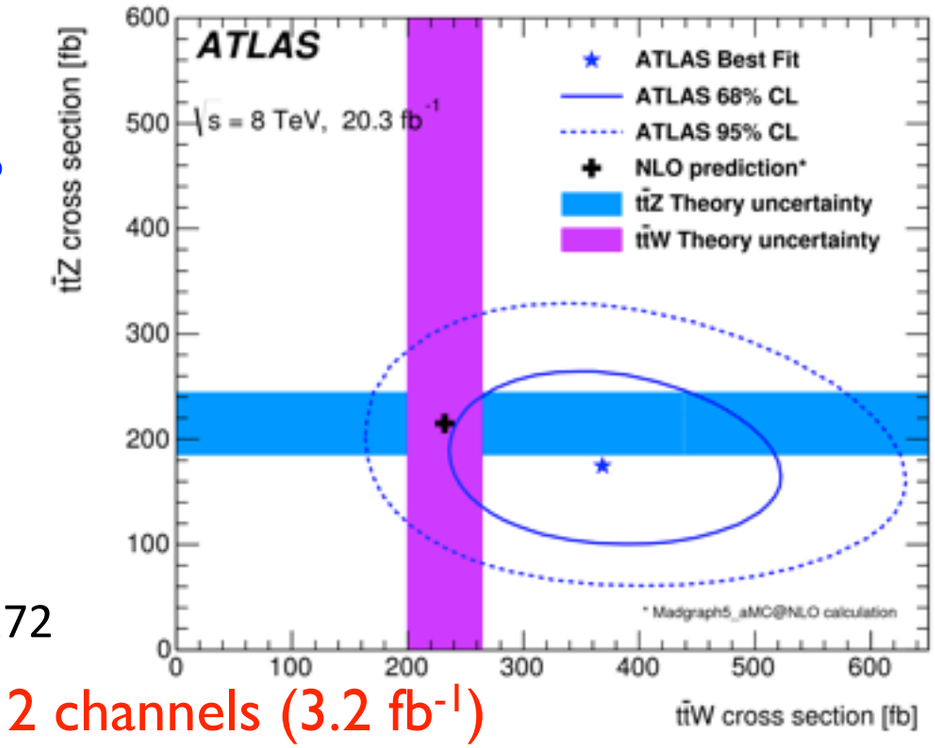

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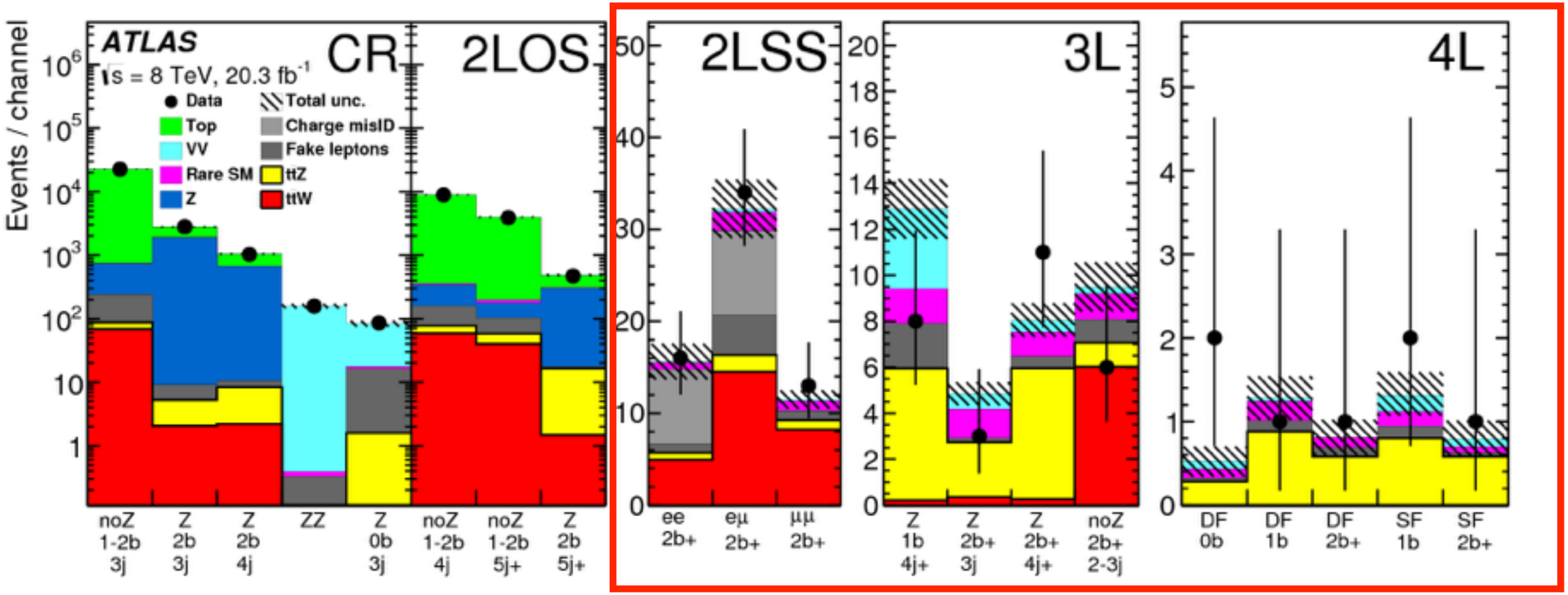
Run 2 channels (3.2 fb^{-1})



Run 2 analysis channels

$t\bar{t}$ Z $t\bar{t}$ W

2lSS two same sign leptons

lepton and charge misID

L H L

3lZveto three leptons outside Z window

$t\bar{t}Z$, $t\bar{t}H$, lepton misID

L L L

L H L L

three leptons two inside Z window **3lZ**

WZ, lepton misID

L L L L

four leptons **4l**

ZZ, lepton misID

Trilepton channel ($t\bar{t}Z$)

Run 2 3.2 fb^{-1}

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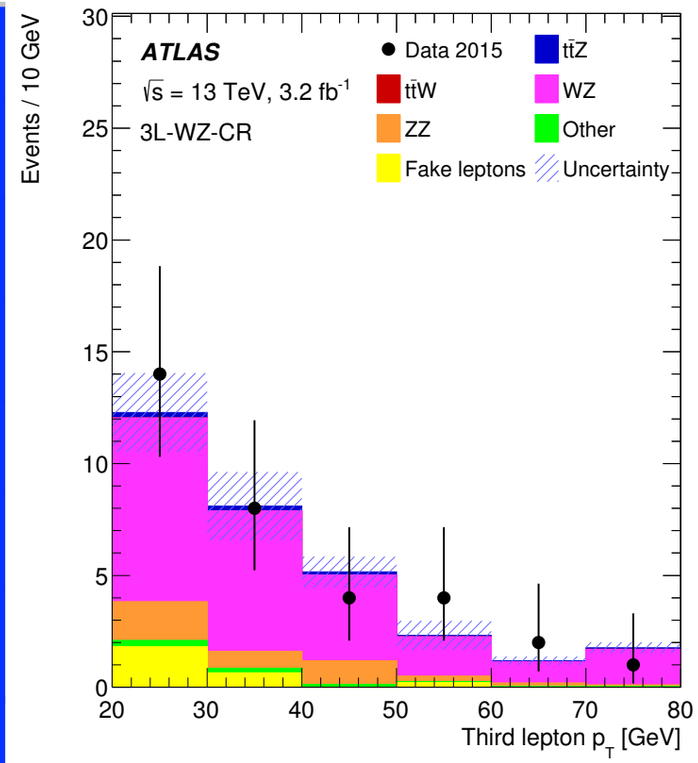
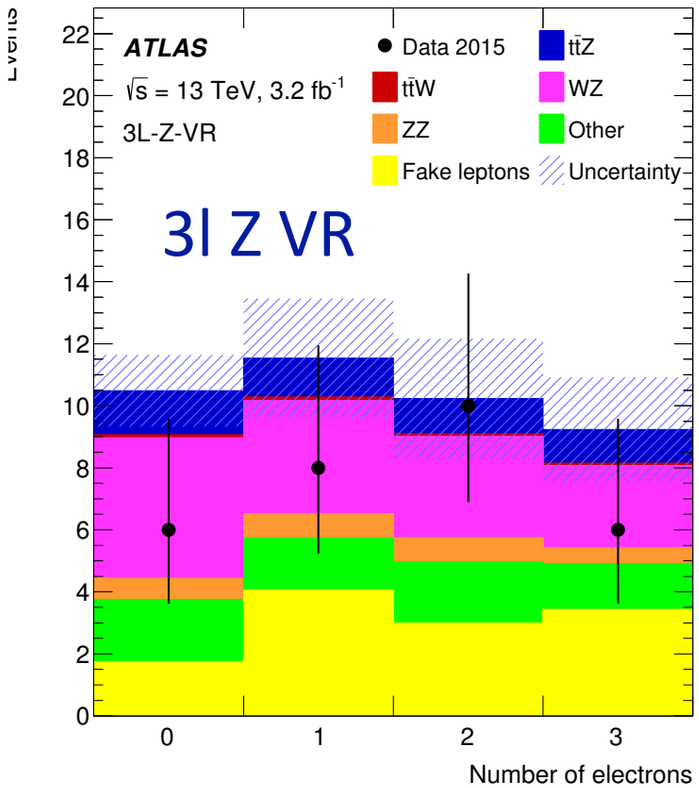
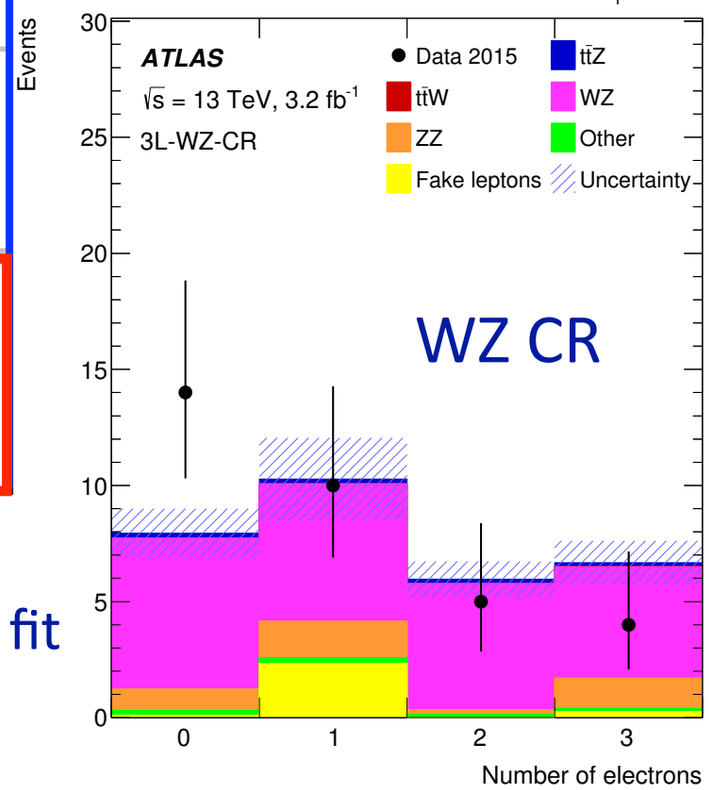
	3lZ
Z-mass window	< 10 GeV
Leptons	leading p_T > 25 GeV
	other p_T > 20 GeV
Sum of charges	±1
Jets	p_T > 25 GeV
B-tagging	77% WP
Signal	$t\bar{t}Z$ dominated
Main backgrounds	WZ: MC and fit in CR fakes: Matrix Method
Fit channels Signal Region	≥4j, =1b =3j, ≥2b ≥4j, ≥2b

- Validation regions are not included in the fit
- Control regions are included in the fit

Background control and validation





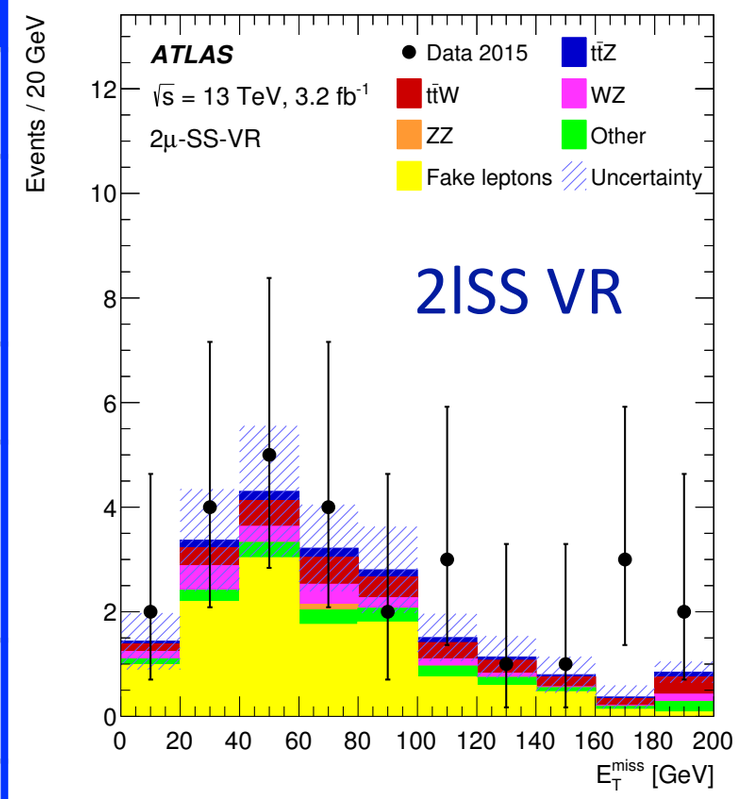


- WZ CR
  - m(ll)< 10 GeV
  - nj=3, =0b
- 3l Z VR
  - m(ll)< 10 GeV
  - nj≤3, =1b or
  - nj=2, =2b

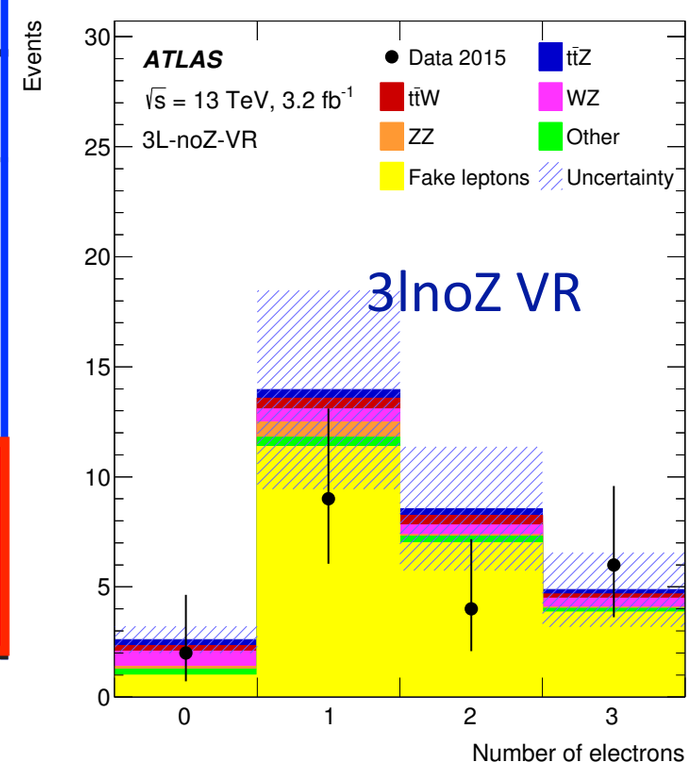
Trilepton and SS dilepton ($t\bar{t}W$)

	3lZveto	2μ
Z-mass	> 10 GeV	
Leptons	leading p_T > 25 GeV other p_T> 20 GeV	muons with p_T > 25 GeV
Sum of	±1	±2
Additional cuts		H_T>240 GeV E_T^{miss} > 40 GeV
Jets	p_T > 25 GeV	
B-tagging	77% WP	
Signal	ttW dominated	
Main background	$t\bar{t}Z$: simultaneous fit $t\bar{t}H$: MC fakes: Matrix Method	fakes: Matrix Method
Fit channels Signal Region	2≤nj≤4, ≥2b	≥2j, ≥2b

Background validation



2lSS VR
- no E_T^{miss} cut
- $p_T^{sublead}$ > 20 GeV
- ≥2b



- 3lnoZ VR
  - m(ll)> 10 GeV
  - 2≤nj≤3
  - =1b

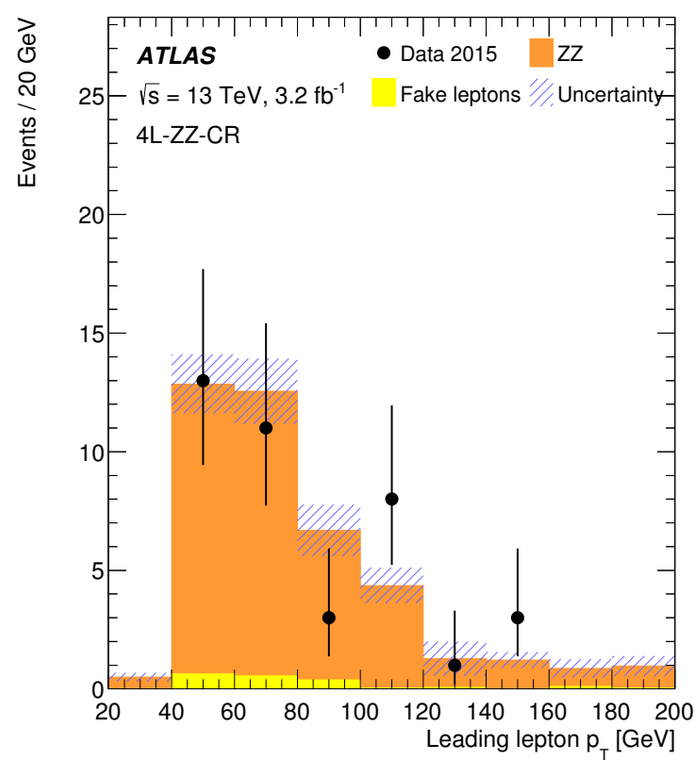
Tetralepton ($t\bar{t}Z$)

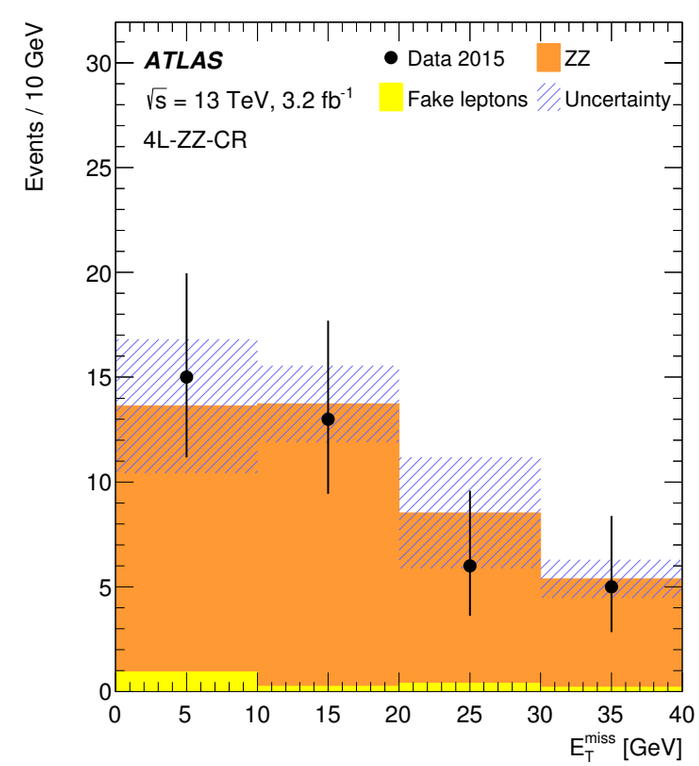
- Two pairs of OS leptons
- Z_1: OSSF pair closest to Z mass

Region	Z_2 leptons	p_{T34}	$\lvert m_{Z_2} - m_Z \rvert$	E_T^{miss}	n_{b-tags}
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	> 35 GeV	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 25 GeV	> 10 GeV < 10 GeV	> 40 GeV > 80 GeV	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	-	> 10 GeV < 10 GeV	- > 40 GeV	≥ 2

Background control: 4l ZZ CR

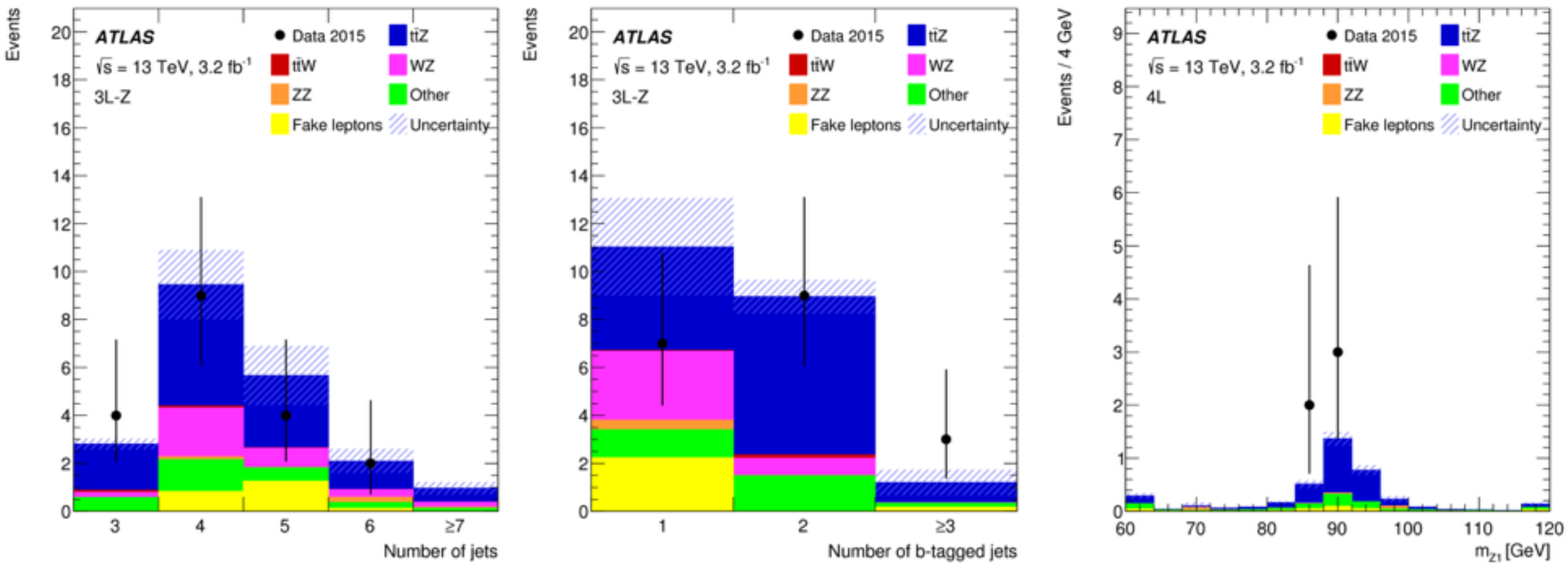
- Main background: ZZ
  - Determined from MC and fit to data in CR
  - 4l ZZ CR
    - 2 OSSF lepton pairs
    - m(ll)< 10 GeV for both pairs
    - E_T^{miss} < 40 GeV





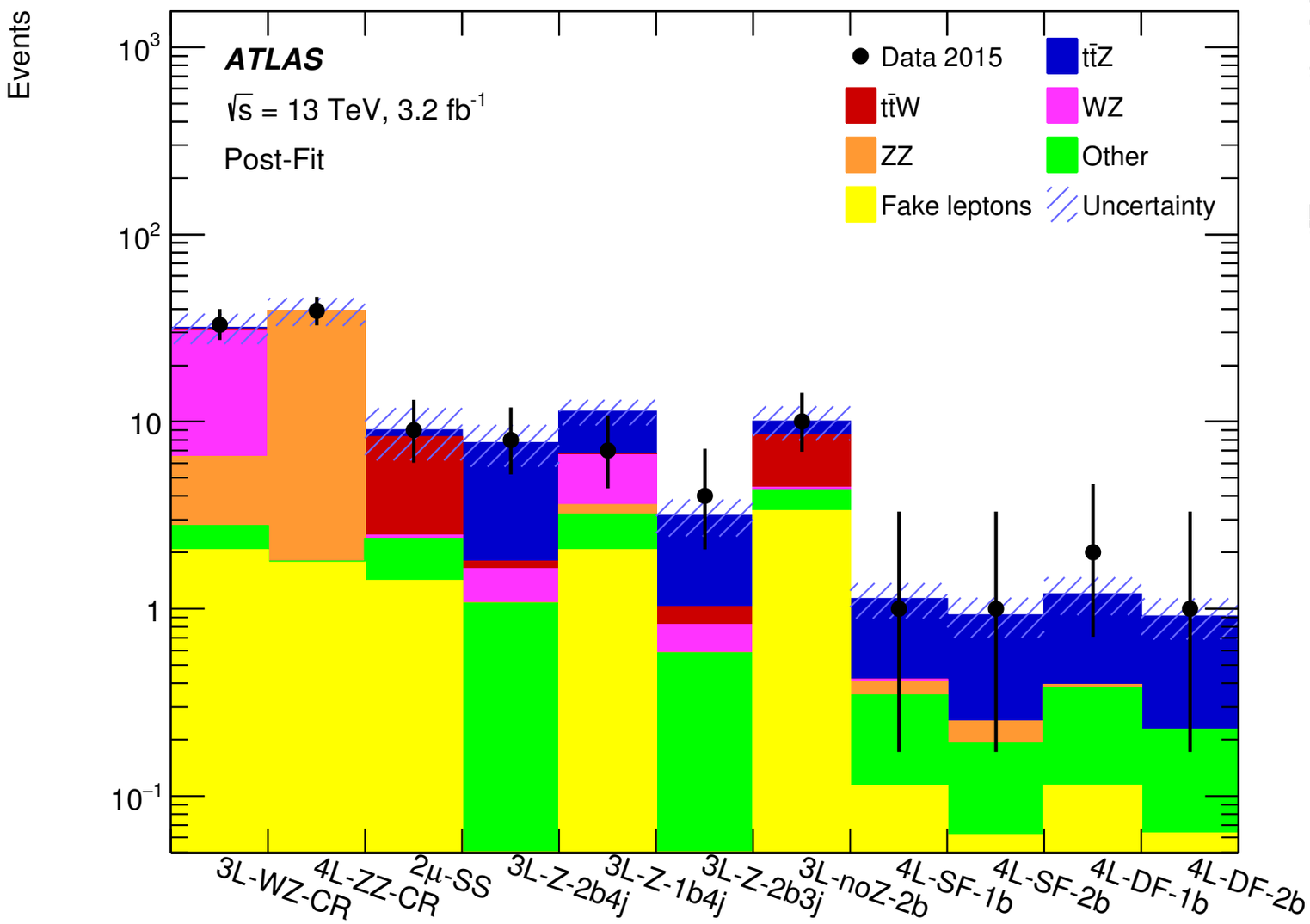
Signal regions

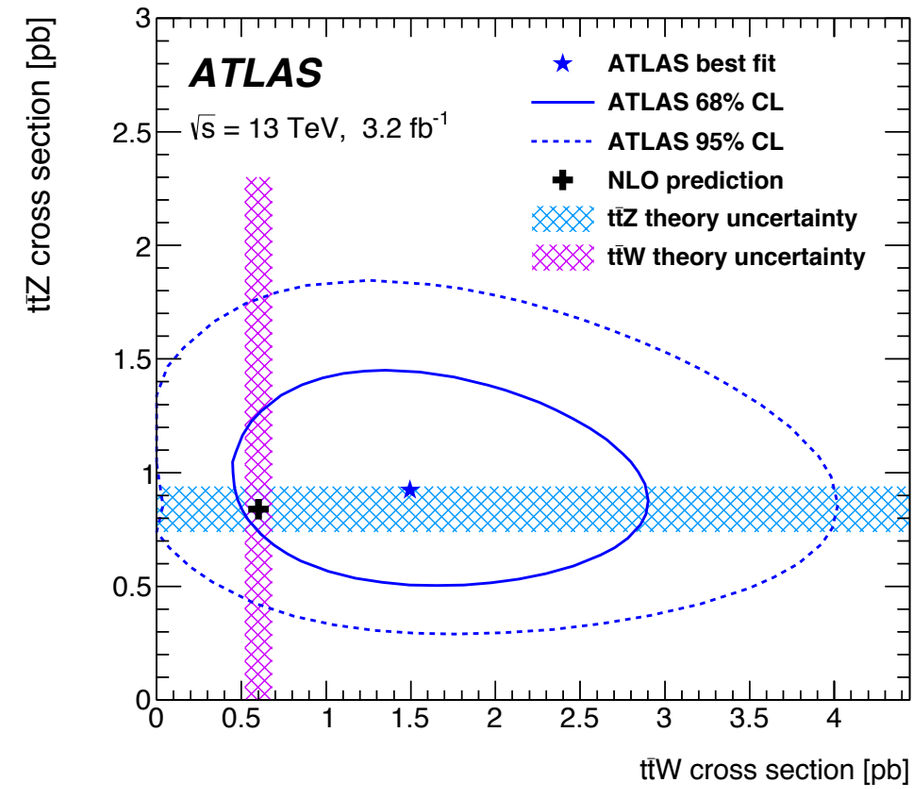
Distributions after selection



Results

- Simultaneous profile likelihood fit in 9 signal and 2 control regions
- WZ and ZZ normalisation are free parameters of the fit





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$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb

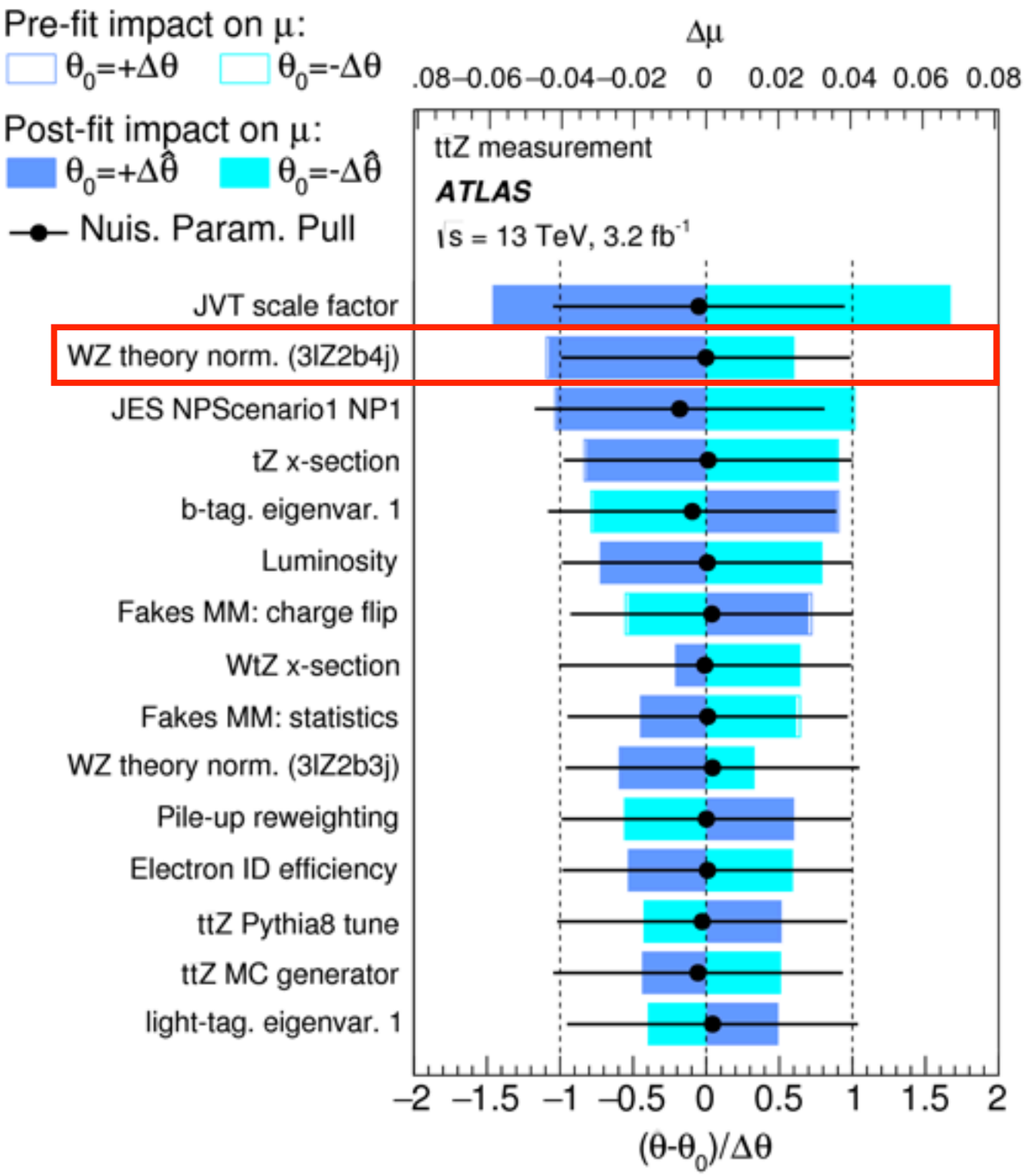
$\sigma_{t\bar{t}W} = 1.5 \pm 0.8$ pb

correlation: -0.13

- Observed (expected) significance over the background-only hypothesis
  - 3.9σ (3.4σ) over the background-only hypothesis for $t\bar{t}Z$
  - 2.2σ (1.0σ) over the background-only hypothesis for $t\bar{t}W$

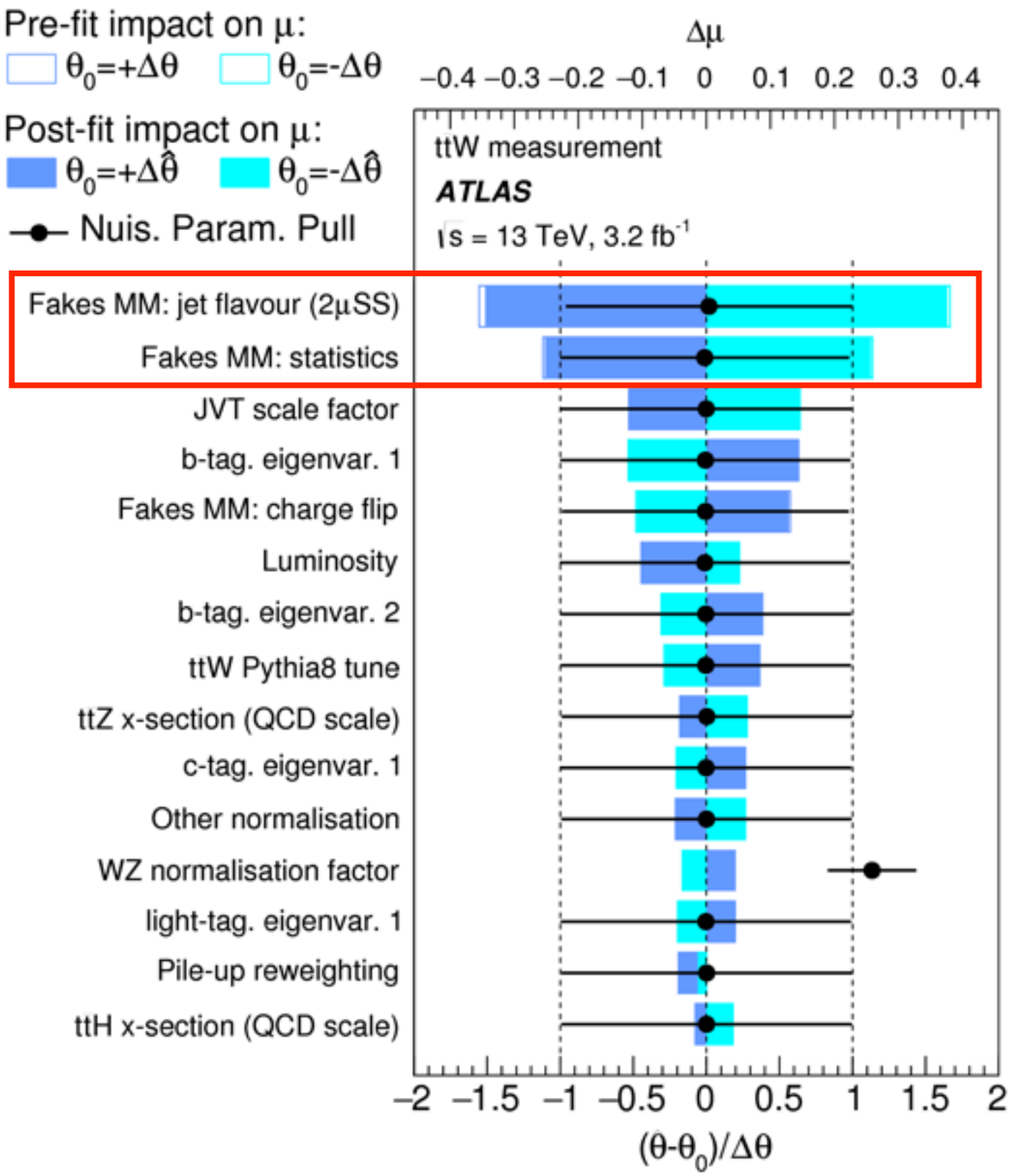
Systematic uncertainties

$t\bar{t}Z$



Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	19%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

Systematic uncertainties ($t\bar{t}W$)



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Total systematic	11%	22%
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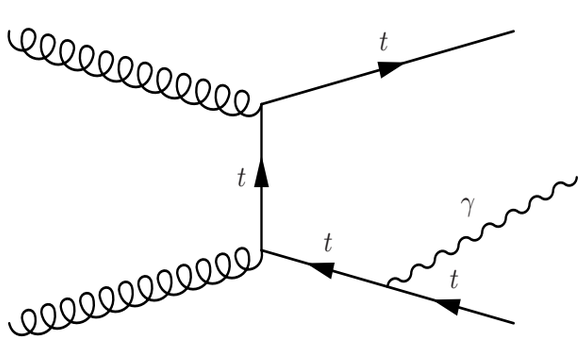
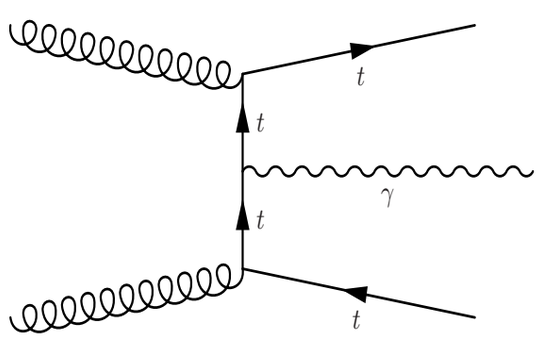
Total	32%	53%

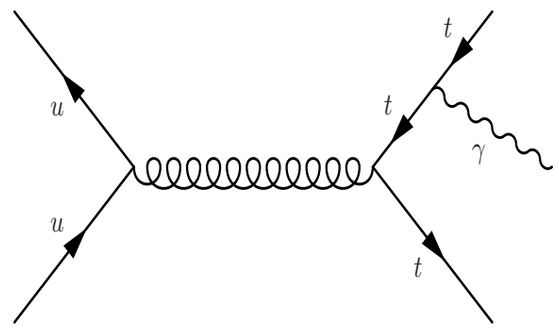
Motivation: $t\bar{t}\gamma$

- Direct probe of V-A and A coupling of the ttγ vertex
- Direct probe of EW photon-top coupling
  - can be modified by anomalous dipole moments of the top quark
- Photon production mechanisms in tt events
  - radiative top production

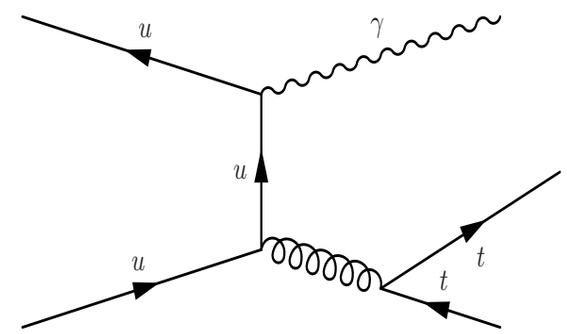
off-shell top radiation





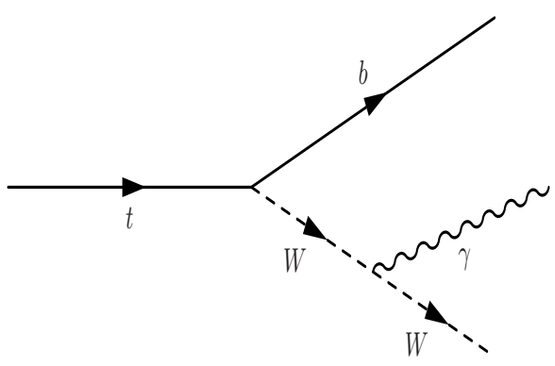


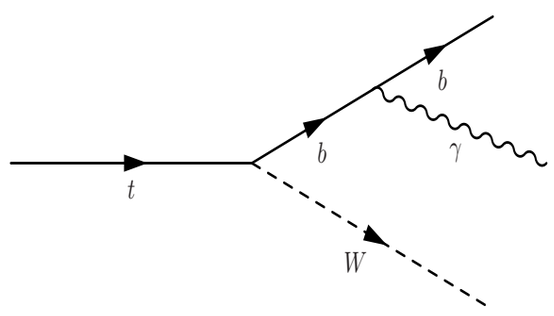
ISR

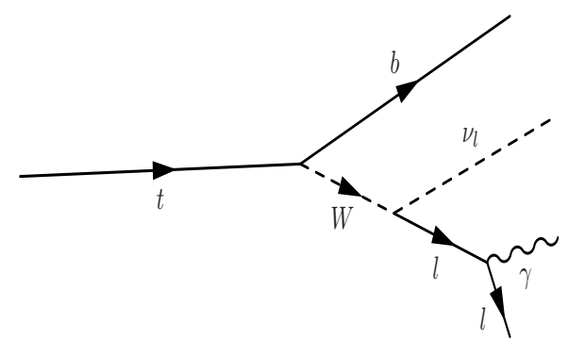


- radiative top decay (γ from W decay chain or t→Wbγ (on-shell decay))

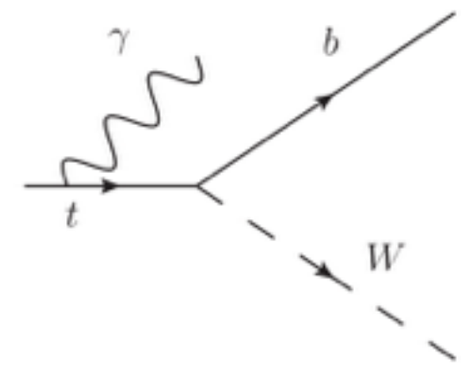
FSR







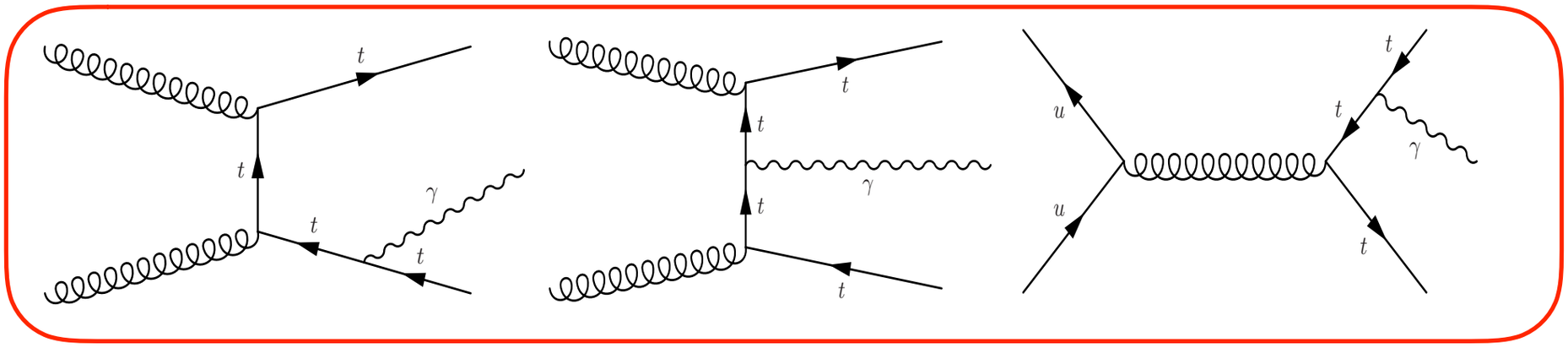
on-shell decay



Motivation: $t\bar{t}\gamma$

- direct probe of V-A and A coupling of the $t\bar{t}\gamma$ vertex
- direct probe of EW top coupling to photon
  - can be modified by anomalous dipole moments of the top quark
- photon production mechanisms in $t\bar{t}$ events
  - radiative top production

off-shell top radiation



- no possibility to distinguish the vertex of photon origin
- selection aims to enhance photons from top quarks and suppress ISR and FSR contributions

Selection

Run I 8 TeV 20.2 fb^{-1}

arXiv:1706.03046 [hep-ex]

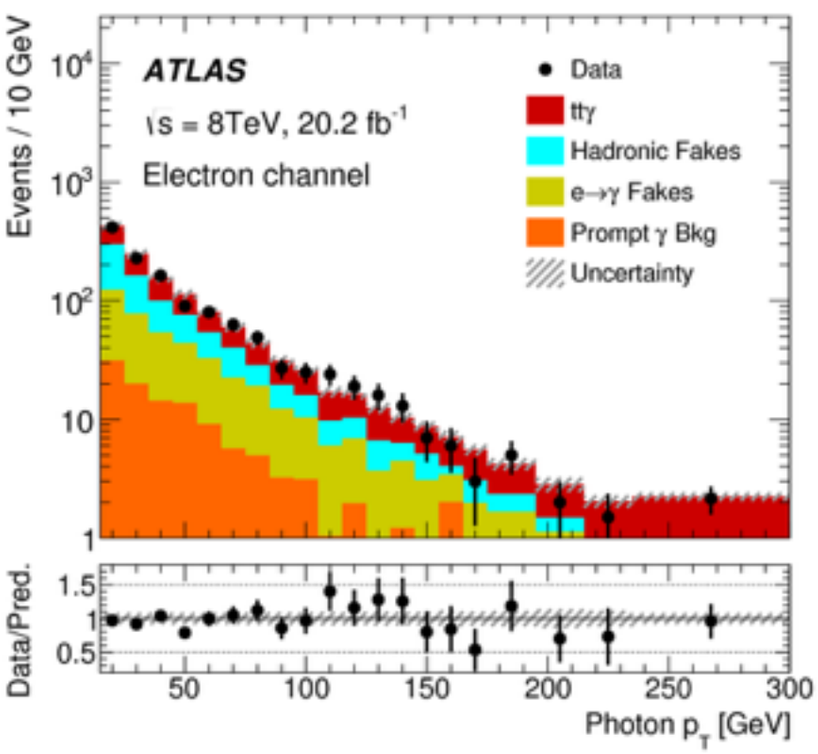
objects	requirement
muon	p_T>25 GeV, $\|\eta\|$<2.5
electron	p_T>25 GeV $\|\eta\|$=[0, 1.37]&[1.52, 2.47]
photon	p_T>15 GeV $\|\eta\|$=[0,1.37]&[1.52,2.37]
jet	p_T>25 GeV, $\|\eta\|$<2.5
b-tag	70% efficiency, rejection factor 140

- Single lepton trigger
- One muon or electron
- ≥4 jets, ≥1 b-jet

μ+jets
- E_T^{miss}> 20 GeV
- E_T^{miss}+ m_T^W >60 GeV

e+jets
- E_T^{miss}> 30 GeV
- m_T^W >30 GeV

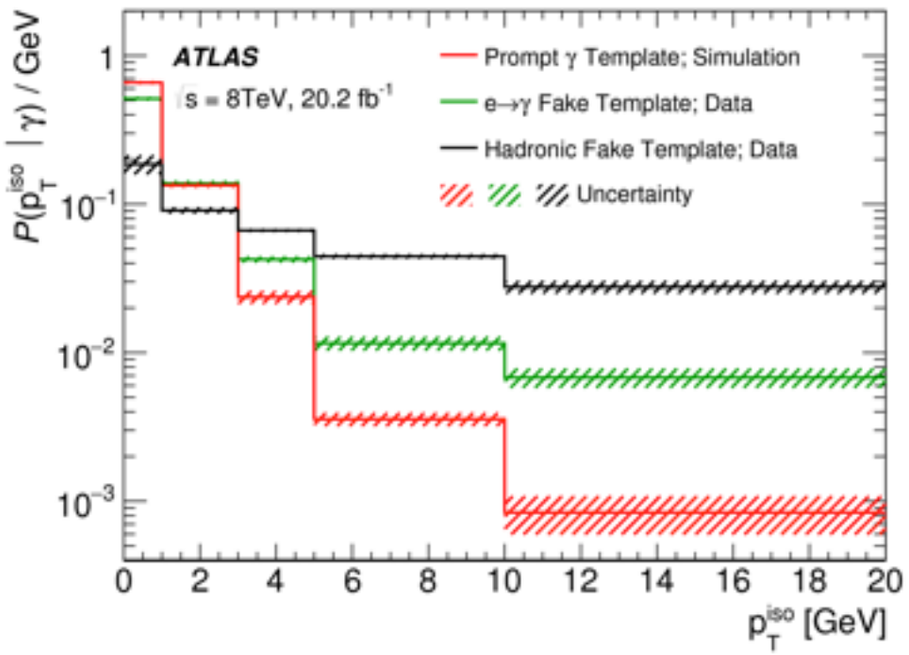
- to suppress lepton fakes

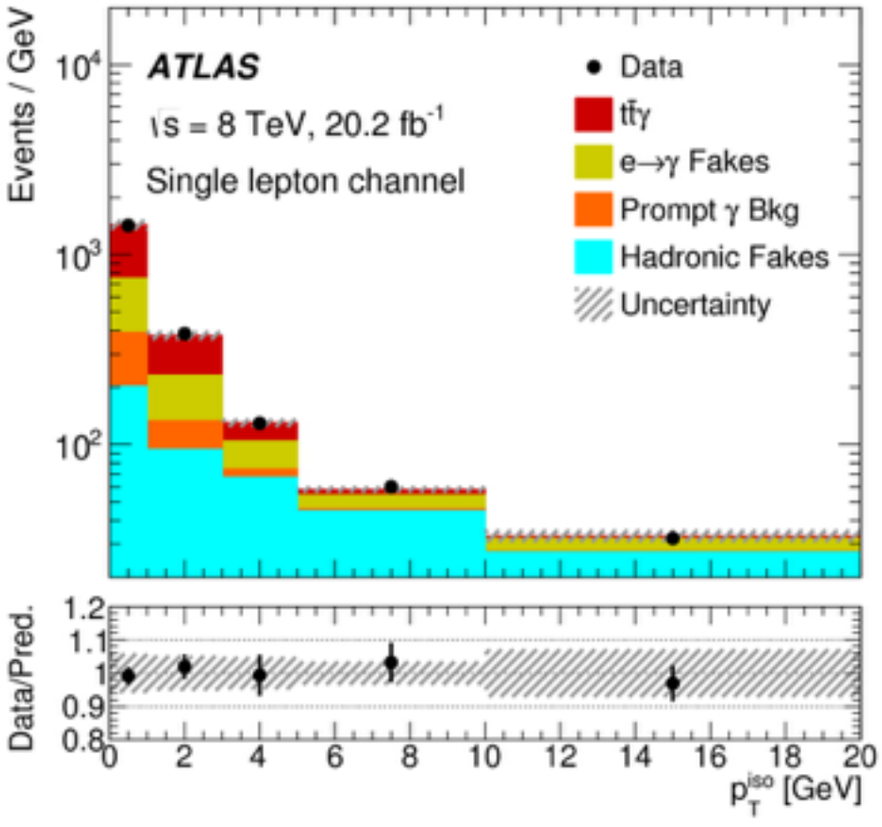


- 1 photon
- no jet within ΔR=0.5 around photon
  - to remove photon radiation from quarks
- ΔR(l,γ) > 0.7
  - to enrich with photons radiated from top
- $m_{e\gamma}$< 86 GeV or $m_{e\gamma}$> 96 GeV
  - to suppress Z+jets events with electron misidentified as photon in e+jets

Analysis strategy

- Extract fiducial cross sections from LH fit to data using templates in p_T^{iso}
  - the sum of track p_T within $\Delta R=0.2$ around the photon
- 3 templates
  - prompt photons
  - hadrons misidentified as photons
  - electrons misidentified as photons
- Normalisation of first 2 are free parameters of the fit
- Bin-by-bin unfolding for differential cross section measurement
  - migration between bins <7%





Background estimate

- Hadron fakes
  - source: $t\bar{t}$ production
- Extracted from a control region
  - at least 1 photon failing at least one of 4 ID criteria on shower shape in layer 1 of EMC
  - strong discrimination between fake and real photons
  - negligible correlation with isolation
- Background shape depends on
  - jet multiplicity, p_T and η of fakes
- Templates in
  - 5 photon p_T bins and 2 η bins

- Electron fakes
  - sources: dilepton $t\bar{t}$ and Z+jets
- Fake rate from a control region
  - 70<m(ee)<110 GeV
  - ratio of Z->e+fake γ to Z->ee as a function of photon pT and η
- Applied to signal region with selected photon is replaced by electron
- Template from Z->e+fake γ selection with
  - E_T^{miss}> 30 GeV
  - $p_T(e)>p_T(\gamma)$

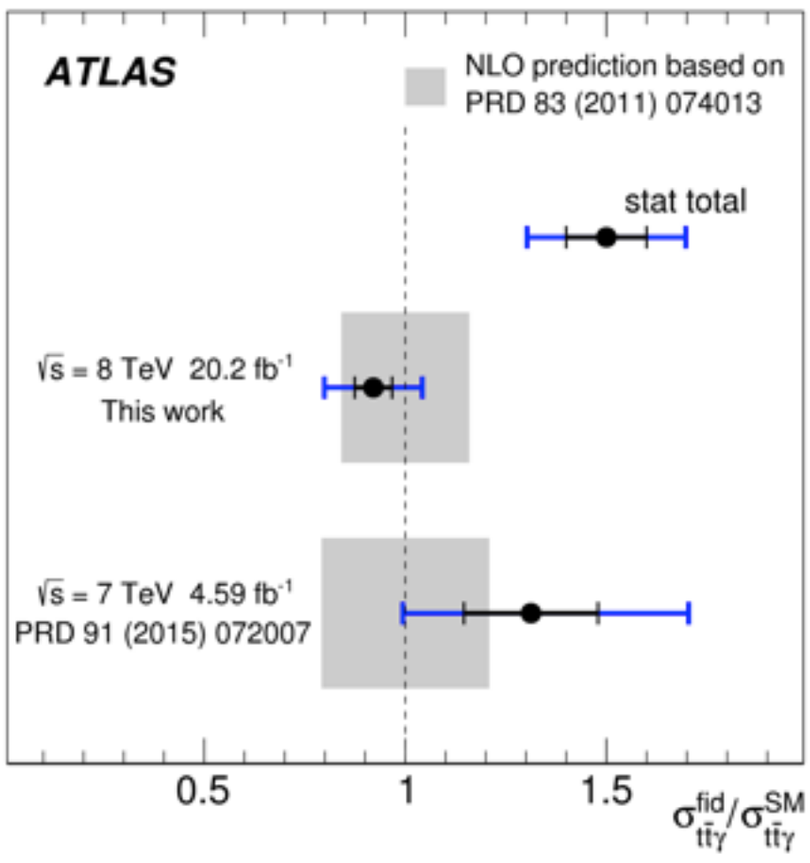
- Prompt photon: Wγ
  - Sherpa with normalisation determined from CR
  - CR: 1≤nJets≤3, nb = 1, m(eγ)<40 GeV
- Prompt other: MC
- Template from ttγ samples

- Prompt photon: multijet
  - lepton fake
  - estimated from Matrix Method

Results

- Fiducial region
  - same as at reconstruction level but no E_T^{miss} and m_T^W cuts
- Theory prediction
  - MadGraph5_aMC@NLO 2.1.0 + Pythia 6
  - LO including $t\bar{t}\gamma$ decay with $\mu=2m_{top}$
  - photon $p_T>15$ GeV, $|\eta|<5$
  - corrected by k factor: 1.90±0.25±0.12
  - ratio of NLO calculation at $\mu=m_{top}$ to LO Madgraph at $\mu=2m_{top}$

Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \to \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma$+jets	4.0
$Z\gamma$+jets	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13



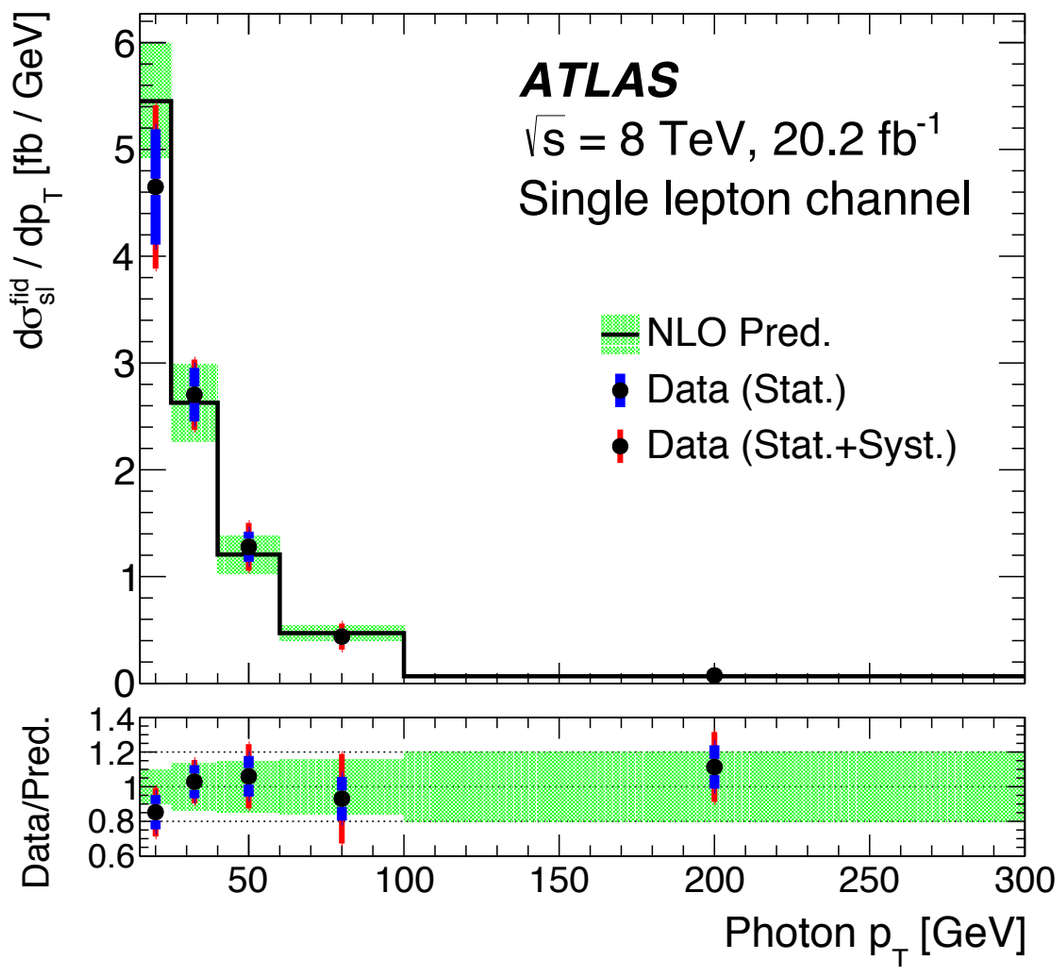
σ_{fid} = 139±7 (stat)±17 (syst) fb

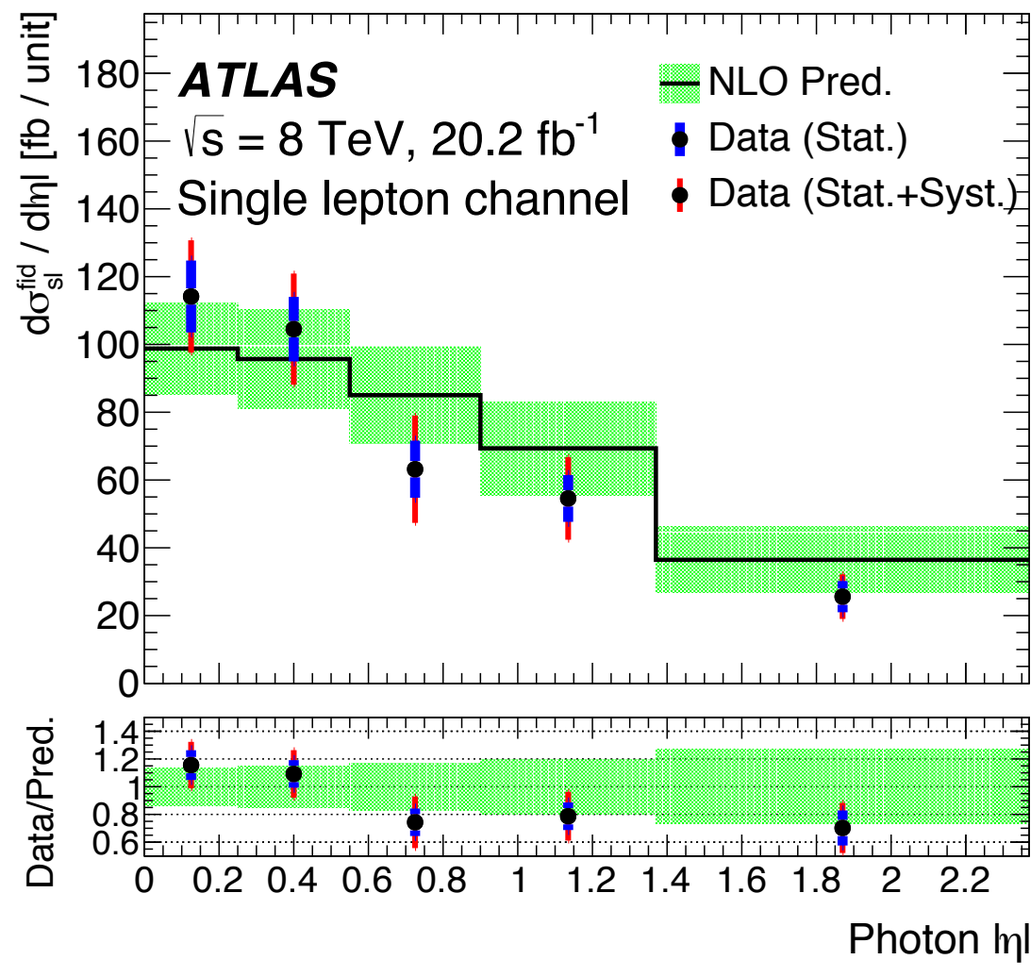
σ_{theory} = 151 ± 24 fb

arXiv:1706.03046 [hep-ex]

Results

First measurement of the differential cross sections





In good agreement with theory prediction

arXiv:1706.03046 [hep-ex]

Conclusions and outlook

- Measurements of the associated production of top quark pair with gauge bosons enter the category of precision measurements
- Results with the 2015+2016 are expected soon
- Available statistics will allow for the measurement of the differential distributions and EFT interpretations to probe signs of physics BSM

Backup

Cross sections

$\sqrt{s}$ and pert. order	process	σ [fb]
8 TeV NLO	$t\bar{t}W^+$	$136.7^{+15.6}_{-15.2}$
8 TeV NLO	$t\bar{t}W^-$	$60.5^{+7.1}_{-6.8}$
8 TeV NLO	$t\bar{t}Z$	$189.8^{+24.5}_{-24.8}$
8 TeV NLO+NNLL	$t\bar{t}W^+$	$130.7^{+6.9}_{-4.9}$
8 TeV NLO+NNLL	$t\bar{t}W^-$	$59.1^{+3.1}_{-2.2}$
8 TeV NLO+NNLL	$t\bar{t}Z$	$203.9^{+13.5}_{-15.8}$
13 TeV NLO	$t\bar{t}W^+$	$356.3^{+43.7}_{-39.5}$
13 TeV NLO	$t\bar{t}W^-$	$182.2^{+23.1}_{-20.4}$
13 TeV NLO	$t\bar{t}Z$	$728.3^{+93.8}_{-90.3}$
13 TeV NLO+NNLL	$t\bar{t}W^+$	$341.0^{+23.1}_{-13.6}$
13 TeV NLO+NNLL	$t\bar{t}W^-$	$177.1^{+12.0}_{-6.9}$
13 TeV NLO+NNLL	$t\bar{t}Z$	$777.8^{+61.3}_{-65.2}$

Table 3. Total cross section for $t\bar{t}Z$ and $t\bar{t}W$ production at the LHC with $\sqrt{s} = 8$ and 13 TeV and MMHT 2014 PDFs. The default value of the factorization scale is $\mu_{f,0} = M/2$, and the uncertainties are estimated through variations of this scale (and of the resummation scales μ_s and μ_h when applicable).

order	PDF order	code	σ [fb]
LO	LO	MG5_aMC	$293.5^{+85.2}_{-61.7}$
app. NLO	NLO	in-house MC	$444.7^{+28.6}_{-39.2}$
NLO no qg	NLO	MG5_aMC	$447.0^{+35.1}_{-40.4}$
NLO	NLO	MG5_aMC	$423.0^{+51.9}_{-49.7}$
NLO+NLL	NLO	in-house MC +MG5_aMC	$466.2^{+22.9}_{-26.8}$
NLO+NNLL	NNLO	in-house MC +MG5_aMC	$514.3^{+42.9}_{-39.5}$
nNLO (Mellin)	NNLO	in-house MC +MG5_aMC	$488.4^{+9.4}_{-8.3}$
$(\text{NLO+NNLL})_{\text{NNLO exp.}}$	NNLO	in-house MC +MG5_aMC	$485.7^{+6.8}_{-15.0}$

Table 3. Total cross section for $t\bar{t}H$ at the LHC with $\sqrt{s} = 13$ TeV and MMHT 2014 PDFs. The results are obtained as in Table 2, but with the default value of the factorization scale chosen instead as $\mu_{f,0} = M$.

Background

- Prompt photons

Process	e + jets	μ + jets
Multijet + γ	7.5 ± 3.6	8.3 ± 5.2
$W\gamma$+jets	65 ± 25	97 ± 25
$Z\gamma$+jets	35 ± 19	38 ± 20
Single top + γ	13 ± 7	19 ± 10
Diboson + γ	2.6 ± 1.5	2.5 ± 1.4

- 8 TeV ttV
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2013-05/
- 13 TeV ttV
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2015-22/
- 8 TeV tty
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2015-21/